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Observations of dew amount using in situ and satellite measurements in an agricultural landscape

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ABSTRACT

Estimating the amount of water on leaf surfaces is an increasing concern for remote sensing and hydrology. Measuring the magnitude and spatial extent of leaf wetness events will provide useful information for water and energy balance modeling and remote sensing. As part of the Soil Moisture Experiments 2005 (SMEX05), the temporal and spatial characterization of leaf wetness over a heterogeneous agricultural domain was investigated. Leaf wetness sensors and physical measurements were collected from 15 June to 3 July 2005 in and around the Walnut Creek Watershed near Ames, Iowa, USA. Comparison of the results of the in situ leaf wetness sensor measurements and the physical sampling revealed a moderate correlation for both corn (*Zea mays* L.) and soybeans (*Glycine max* Merr.). Regression equations were developed to estimate leaf wetness quantity from these leaf wetness sensors and combined with a vegetation leaf area index map to produce a spatial leaf wetness product hourly during the experiment with an error of approximately 0.05 kg/(m^2 LAI). Using this strategy, future efforts in spatial hydrologic modeling and remote sensing would be able to incorporate quantitative estimates of leaf wetness amount in watershed scale studies using only in situ measurements.

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1. Introduction

The study of dew has focused primarily on its presence and duration as an indicator of plant pathogen activity (Monteith, 1957; Royle and Butler, 1986; Sutton et al., 1984) because many plant pathogens require moisture for germination (Wallin, 1963). As a result, most modeling activities and sensor technologies have focused on occurrence and duration of surface wetness (Gillespie and Kidd, 1987; Wilson et al., 1999). Wilson et al. (1999) developed a model that simulates dew formation and duration throughout the leaf canopy. Magarey et al. (2005) provide an overview of the development of dew monitoring that indicates a preponderance of research on dew duration rather than quantity.

As remote sensing of soil moisture has evolved from concept to satellites, research has begun to consider the full range of factors that can affect the observation, which includes leaf wetness resulting from dew-fall, distillation, and guttation (Monteith, 1957). The effect of dew on microwave signals used for soil moisture remote sensing has been mixed. Initial studies (Jackson and Moy, 1999; Wigneron et al., 1996) reviewed previous research utilizing passive microwave remote sensing and concluded that there would be little to no effect at the L-band. Conversely, Pinter (1986) showed that dew had a significant effect on canopy reflectance across a range of frequencies by using radiometers during a diurnal cycle. More recent studies (Hornbuckle et al., 2007, 2006) determined that L-band radiometers (those used for soil moisture remote sensing) are reactive to the presence of leaf wetness. Wood et al. (2002) determined that leaf wetness affected the relationship between backscatter coefficient of active microwave remote sensing and crop characteristics such as yield and biomass. The magnitude of influence that dew may have has yet to be determined, but first a methodology for estimating large-scale dew magnitudes is necessary.

Estimating the quantity of dew temporally on a daily scale and spatially on a regional scale will be valuable in further research and potentially in operational practices (such as irrigation scheduling and fertilizer applications), not only for remote sensing, but for modeling. The necessary input for any study of the effect of leaf wetness on remote sensing requires an estimation of the leaf wetness within the vegetation canopy on a scale at which satellite

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radiometry is available. Aircraft based microwave radiometers, such as those used during Washita '92 (Jackson and Le Vine, 1996) and SMEX02 (Bindlish et al., 2006), can retrieve soil moisture on the order of >100 m, while truck based radiometers can monitor as small as 10 m, depending on deployment. Passive satellite remote sensing is a much larger scale (~50 km) but future technologies could increase the resolution to 10 km by combining passive and active microwave remote sensing. Even at 10 km, these scales are still too large to be considered hydrologically homogeneous, due to the heterogeneity of the land cover, topography, and soil. From a practical perspective, in an agricultural domain the largest scale that can be considered homogenous might be a farm field on the order of 800 m (Cosh and Brutsaert, 1999). This scale is also the maximum scale for which dew could be considered homogenous considering the land cover, topography and soil management practices which can influence the micrometeorology and dew formation. Therefore, a method of estimating field scale leaf wetness is necessary for characterizing units at this scale. From this scale, modeling and aggregation techniques must be used to scale up to the remote sensing footprint (Famiglietti and Wood, 1994; Hu et al., 1999).

The goal of this study was to provide quantitative leaf wetness information as part of a soil moisture remote sensing experiment, SMEX05 (Jackson, 2005). This was accomplished by combining continuous observations by in situ leaf wetness sensors with limited physical sampling of leaf wetness from early morning to a dry condition. Extrapolation of this study to include intercepted precipitation and/or irrigation is not recommended because of the different methods of liquid deposition. Neither precipitation nor sprayed irrigation forms passively on the surface of the plant, but rather actively impacts the surfaces and accumulates in a different fashion from dew on both the leaf surfaces and on the stems and collars. Only leaf wetness as a result of dewfall will be studied here. The desired end result is a temporal mapping of leaf wetness in the plant canopy on a large scale with minimum calibration and physical data collection.

2. Study region

To study the development and magnitude of dew in an agricultural region, an experiment was organized as part of SMEX05 near Ames, Iowa in and around the Walnut Creek watershed (41.9821°N, 93.6924°W). The area is dominated by agriculture with 34% of the land planted in corn (*Zea mays* L.) and 30% planted in soybean (*Glycine max* Merr.) (Yilmaz et al., 2008). Both crops were planted in 30 in. rows. The corn fields were planted around approximately Day of Year 100 and the soy bean fields were planted within an week of each other around Day of Year 126. There is little topography (less than 5%) and the climate is humid, receiving 835 mm of precipitation per year (Hatfield et al., 1999). This experiment was designed primarily to validate the ability of the WindSat satellite passive microwave instrument (Gaiser et al., 2004) to retrieve surface soil moisture.

As part of this validation experiment, an aircraft-based WindSat simulator, the Airborne-Polarimetric Microwave Imaging Radiometer (APMIR), was flown in coordination with ground-based soil moisture sampling activities to provide scaling from the small field scale to the regional satellite scale (Jackson, 2005). The WindSat instrument is a multi-frequency polarimetric microwave radiometer developed to study scattering on the sea surface for use in estimating wind speed. The WindSat radiometer operates at nominal frequencies of 6.8, 10.7, 18.7, 23.8, and 37 GHz. It is the 6.8 and 10.7 GHz frequencies, which can also be sued to estimate soil moisture. A full description of WindSat can be found in (Gaiser et al., 2004). The local overpass time of WindSat in Ames, Iowa was approximately 6:30 a.m. CST; therefore, aircraft and ground sampling was coordinated to occur between 5:30 and 8:30 a.m. CST. Assessing the quantity, spatial variability, and duration of leaf wetness was accomplished by a sampling team, which maintained leaf wetness sensors and collected gravimetric samples of leaf wetness across the region each day.

3. Sampling protocol

For each sampling field, three locations were selected for replication. A total of five fields were included in this study, WC10 (Walnut Creek, Field 10, Corn), WC36 (Corn), WC52 (Corn), WC11 (Soybean), and WC15 (Soybean). Fig. 1 shows the locations of these sampling sites within the study region, as well as the land cover during the SMEX05 study period. Each sampling location was located adjacent to a leaf wetness sensor installation, which varied from one to four leaf wetness sensors (Model 237-L, Campbell Scientific, Logan, UT, USA) installed at an angle of 45° to horizontal and facing north. The installation heights were adjusted periodically throughout the study period in accordance with crop growth, with two different configurations: at 1/3 and 2/3 of the canopy height for the two-sensor configuration or at 1/2 canopy height in the one sensor configuration.

The leaf wetness sensors consist of an interlacing circuit board, which is open (electrical resistance is infinitely large). As moisture beads form on the surface of the circuit board, the resistance decreases (to ~1 Ω for a very heavy leaf wetness event). These sensors are intended to report a percent of time the sensor surface is wet (percent of time resistance less than 150 kΩ). In this study it was hypothesized that they could also be used to estimate leaf wetness quantitatively if calibrated for a specific installation. For

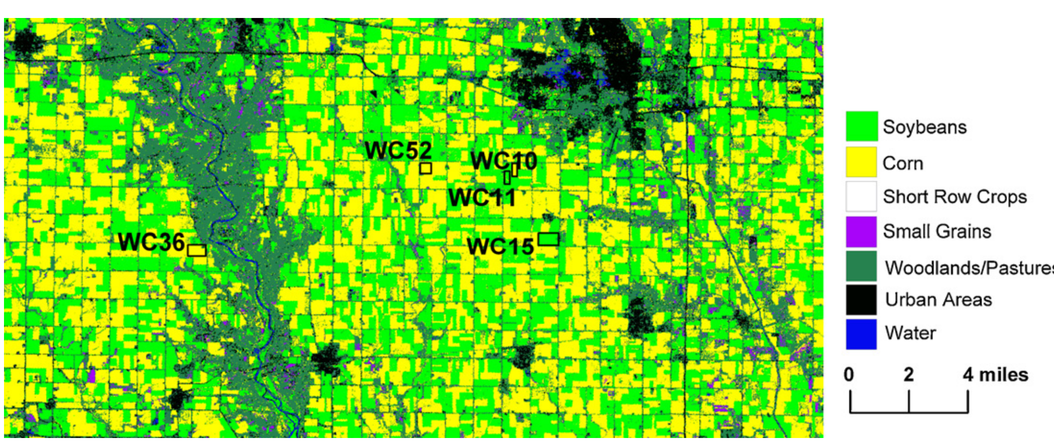

Fig. 1. Land cover map of the SMEX05 study region with the five study fields.

this experiment, the sensors were treated with latex paint of a proprietary composition (Davis and Hughes, 1970), whose specific properties were designed to maximize sensitivity to surface wetness (Lau et al., 2000). Three to five coats of latex paint were oven-dried for 24 h between each coating in accordance with the proprietary techniques developed by Davis and Hughes (1970) before deployment in the field. Physical location within the leaf canopy can also affect performance of a sensor. Several sensors were excluded from this experiment because of aberrant behavior in relation to the other sensors and observations made by individuals in those fields, such as no significant resistance changes in spite of significant dew events. This behavior was most likely a result of circumspect installation within the canopy. Because the canopy is growing and the sensor needs to be moved to maintain a position in relation to the overall canopy height there is an increased likelihood of inconsistent or temporally unstable readings.

From 6/15/08 to 7/3/08, physical samples of leaf wetness were collected for a mixture of corn and soybean fields. A summary of the average vegetation characteristics for each of the sampling dates is shown in Table 1. Corn fields were often sampled twice in the same day because the leaf wetness duration was longer and there was still measurable wetness after the soybean fields had dried out. This is primarily due to the low profile of the soybean plant in relation to the row spacing. Much of the soybean plant is exposed to sunlight, while the bottom leaves of a mature corn plant are often in shadow for the entire day. In this experiment, corn was in its vegetative stage (pre-tassel) and soybeans were also in the vegetative stage (pre-flower); therefore, the only changes were additional leaves and height. Individual corn and trifoliate (3) soybean leaves at 1/3 and 2/3 of the canopy height were swabbed using pre-weighed paper towels until dry, taking care that as much moisture as possible on the plant was captured. These paper towels stored in airtight plastic bags and reweighed later in the day. The difference was estimated to be the captured leaf wetness. For soybeans, separate measurements of both the top (adaxial) and bottom (abaxial) of three leaves were sampled. For corn leaves, the top (adaxial), bottom (abaxial), and collar of the leaf were sampled and weighed separately as well. The leaves were collected and single-sided leaf areas were measured using standard imaging software (Scion Image for Windows[1]). Using plant density per square meter, leaf count and average leaf area were used to calculate the total leaf wetness in kg/m^2. The minimum amount measured during the campaign was approximately 0.002 kg/m^2. In addition, for the sampling location, the leaf area index (LAI) was measured using a LAI-2000 plant canopy analyzer (Li-Cor, Inc., Lincoln, Nebraska, USA)[1] at each sampling location following procedures in Jackson (2005). Several of these sampling locations coincided with surface energy flux stations, which collected data for modeling the atmosphere-land surface interface. The surface flux data were used to model the onset, magnitude, and duration of leaf wetness for a select few sites in Kabela et al. (2009).

4. Analysis

It would be very difficult to deploy and maintain an accurate dew sensor network for more than a field scale (~800 m) dew estimate. A vegetation parameter that is easily measured at large scales would be the most efficient method for extrapolating leaf wetness estimation to the large scale. Leaf area index is the best-suited index, because it is a parameterization of the leaf surface area, on which the leaf wetness forms. For SMEX05 (Yilmaz et al., 2008) conducted a field study in the Walnut Creek watershed, and generated two maps (Landsat TM5 Path 27/Row 31 on 6/6/05 and Path 26/Row 31 on 7/17/05) of LAI based on NDVI (Daughtry et al., 1992). Linearly interpolating between these two dates provides a daily estimate of LAI with a 30-m resolution. Fig. 2 contains LAI measured at the surface and the daily satellite-derived LAI estimates. There were moderate to strong correlations ($R^2 > 0.50$) for corn and soybeans. Fig. 2 indicates linear relationships between the satellite measurements and the ground based data, so a simple linear conversion should be applicable. For this study, the satellite-derived LAI was used for further analysis. From physical sampling, the total leaf wetness (TLW) in units of kg per square meter of ground surface were calculated for each measurement and then divided by the satellite based leaf area index (TLW/LAI) from the nearest 30 m pixel. This value was then compared to the local leaf wetness sensor measurement (LWS) at the nearest time record. Fig. 3 shows the relationship between TLW/LAI and LWS for corn (a) and soybean (b). The relationship for

[1] Mention of this product does not constitute an endorsement.

Table 1
Average vegetation characteristics for the SMEX05 leaf wetness study. LAI was collected using a LiCor-LAI2000, row density is number of plants per 36 in. and leaf count per plants.

Field	Day of Year in 2008	Height (in.)	Leaf count	Row density (36 in.)	LAI
WC11	166	6.7	3.0	19.3	0.4
	170	8.0	4.0	20.3	0.5
	174	8.0	6.0	19.0	0.8
	184	13.0	7.0	27.0	1.7
WC15	167	5.7	3.0	23.7	0.5
	173	10.0	7.0	24.3	0.8
	177	13.3	7.7	32.3	1.3
	183	15.7	7.7	30.5	1.8
WC10	166	33.8	11.3	7.5	1.4
	170	43.0	12.8	6.0	2.0
	174	54.3	12.7	6.7	2.4
	184	80.0	14.0	6.0	3.5
WC36	168	26.0	10.3	5.7	0.9
	172	33.3	10.3	6.0	1.6
	178	50.7	12.3	6.0	2.6
	181	48.0	12.0	6.5	2.4
WC52	167	24.5	10.3	6.0	0.7
	171	32.5	10.5	6.0	1.4
	177	55.0	12.5	6.0	2.4
	181	61.0	14.0	6.0	1.7
	182	57.0	13.0	6.0	2.8

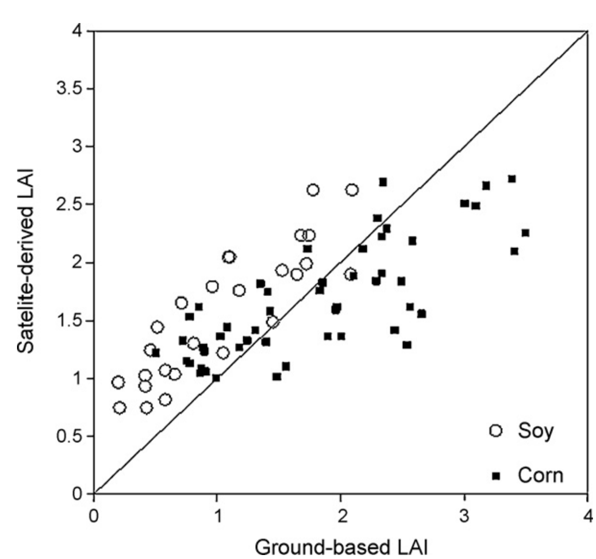

Fig. 2. Ground-based (total) LAI measurements compared to satellite-derived (green) LAI for the nearest 30-m pixel.

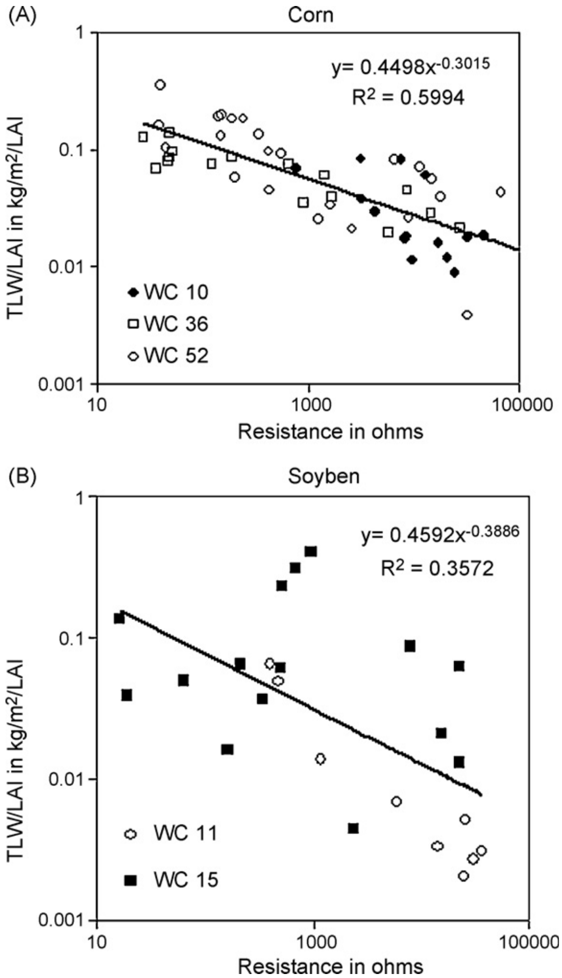

Fig. 3. Leaf wetness sensor resistance versus total leaf wetness/LAI for five study fields within the SMEX05 domain.

corn was obvious with clear linear characteristics ($R^2 \sim 0.59$) for the range of resistance 10^2 to 10^5 Ω, whereas the soy comparison was less well behaved ($R^2 \sim 0.38$). It should be noted that most of the error in the soybean relationship comes from one field (WC15). In this field, the soybean planting density was higher than in WC11 and the average plant height was greater during the middle of the experiment as shown in Table 1. As a result of the dense canopoy, the sensor installation may have failed to properly monitor the leaf canopy and its micrometeorology because of leaf interference with the sensor. The soybean plants were often only 20 cm high with 30 cm spacing. The corn canopy was more 'closed' allowing for a more homogeneous sub-canopy environment in which to install the leaf wetness sensors, resulting in a less variable relationship. Fig. 3 also shows the regression equations derived from these comparisons, which can be used to convert leaf wetness sensor data into leaf wetness estimates. The regression equation for corn yields a root mean square error (RMSE) of 0.047 kg/(m^2 LAI), which for a high stand of corn (LAI $\sim$ 5) would translate to a RMSE of approximately 0.2 kg/m^2 of total leaf wetness. For soybeans, the regression yields a RMSE of 0.054 kg/(m^2 LAI), which is significantly affected by the inclusion of WC15 in the calculations. Soybeans during this time period averaged an LAI of approximately 1.0, therefore an overall RMSE of 0.05 kg/m^2. Soybean total leaf wetness values peak at approximately 0.3 kg/m^2, while corn total leaf wetness values were peaking almost at 1.0 kg/m^2. As could be concluded from the regression relationships, corn can be more accurately estimated than soybean considering the larger values and better correlation between sensor and measured values, at least during the early part of the growing season when these comparisons were made.

Extrapolating these findings relies on the assumption that leaf wetness occurs on a large scale and is homogeneous for the scale of consideration within similar crop canopies. To investigate this assumption, further data are necessary than the sampled fields. A total of 42 automated leaf wetness sensors were deployed in 18 different fields, allowing for some replication in intensively observed fields. The average correlation coefficients for the leaf wetness sensor data records among fields were 0.483 for corn with a standard deviation of 0.22 and 0.516 for soybean with a standard deviation of 0.24. This supports the assumption that there is moderate homogeneity for leaf wetness in the domain. Then, leaf wetness amount can be generated for each time period of interest using the average leaf wetness sensor resistance for corn and soybean and the calibration equations (shown in Fig. 3) for leaf wetness quantity. These calibration equations are considered valid for these sensors in fields with these crops at this stage of growth. Fig. 4 shows an example of four hourly maps for June 30th, at 6 a.m., 7 a.m., 8 a.m., and 10 a.m. Since each sensor experiences a unique microenvironment, best results will occur when sensor-specific and site-specific relationships between wetness sensor resistance and leaf wetness amount are used.

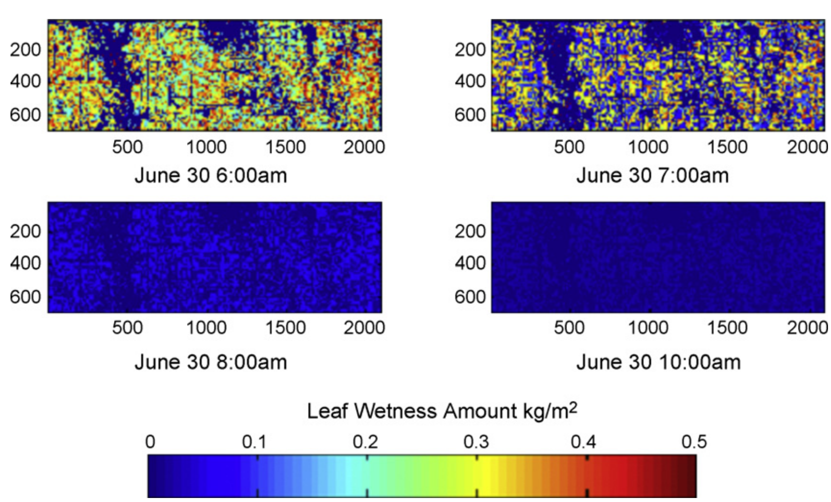

Fig. 4. Four hours of leaf wetness quantity for 30 June 2005, using the average resistance for soybean and corn calculated from all leaf wetness sensors.

5. Conclusion

In this study, we demonstrated that it is possible to estimate leaf wetness amount using leaf wetness sensors and establish moderate homogeneity in leaf wetness amount among fields of the same crop at the watershed scale. At this stage, it appears that physical sampling of leaf wetness is necessary in order to calibrate each sensor installation, and that these sensors should be maintained at a proper height within the uniform crop canopy so that their relationship with respect to the top of the canopy is maintained. Recalibration may be necessary when fundamental changes in crop phenology occur.

Once calibration equations are generated, the sensor readings can be used to extrapolate leaf wetness amount to the surrounding area, in this study approximately 125 km^2. Hourly maps were developed using this sensor history for those days with significant leaf wetness events. These maps are capable of contributing to the modeling of the land surface and the complex water and energy budgets that have no current resource for quantitative leaf wetness monitoring outside of micro lysimetry. This study indicates that with careful installation, calibration, and maintenance, leaf wetness quantity imagery can be developed for remote sensing research using generally available vegetation information, namely LAI.

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